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RESEARCH MEMORANDUM

COMPONENT PERFORMANCE INVESTIGATION OF J71 EXPERIMENTAL TURBINE

X - EFFECT OF FIRST-STATOR ADJUSTMENT; INTERNAL FLOW CONDITIONS OF J71-97 TURBINE WITH 132-PERCENT-DESIGN STATOR AREA

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The changes in the internal flow conditions resulting from adjusting the first-stator throat area of the J71 experimental three-stage turbine were investigated. Presented herein are the experimental results of interstage flow measurements obtained from a radial survey investigation conducted on this turbine when equipped with a first-stage stator with a throat area increased to 132 percent of the design area and operated at a single predetermined turbine match point. Radial variations and mass-averaged values of stage efficiency were determined, along with Mach number and flow-angle distributions behind each blade row.

The mass-averaged first-, second-, and third-stage efficiencies were 0.850, 0.815, and 0.784, respectively. Regions of deficiency were noted near the hub and tip regions for all three turbine stages. The corresponding over-all mass-averaged efficiency was 0.831. The radial survey results for the turbine with the 132-percent-design first-stator area are compared herein with those previously obtained with the same experimental turbine equipped with first-stage stators with throat areas nominally 70, 87, and 97 percent of the design area, each turbine configuration being investigated at or near its turbine match point. The individual stage efficiencies varied considerably for each of the four turbines. Also, the efficiency of any particular stage varied widely as the first-stator area was changed. However, the over-all turbine efficiency varied only about three points over the wide range of first-stator areas investigated.

INTRODUCTION

The NACA Lewis laboratory is currently studying the effect of first-stator throat area changes on the component performance of an experimental J71 three-stage turbine. References 1 to 4 present the over-all performance characteristics of this turbine when equipped with first stators with throat areas nominally 70, 87, 97, and 132 percent of the design area. The maximum obtainable over-all turbine efficiency over the entire range of first-stator area adjustment varied only between 0.87 and 0.89.

A compressor-turbine match-point analysis was conducted in reference 4, based on an arbitrary mode of engine operation during which the compressor was maintained at constant equivalent design conditions. In an effort to determine the change in the internal flow conditions effected by these first-stator area changes, the 70-, 87-, and 97-percent turbines were operated at or near this match point, and a radial survey investigation was conducted. These results are presented in references 5 to 7.

This report is the last of the series and presents the results of a survey of the 132-percent turbine operating at its compressor-turbine match point. The results of the present investigation are compared with those previously obtained for the 70-, 87-, and 97-percent turbines. The results presented herein are not considered quantitative; but, since the methods used for all four turbine configurations were similar, they can be interpreted as indicating trends of comparative performance.

SYMBOLS

c	blade chord, ft
p	pressure, lb/sq ft
s	blade spacing, ft
T	temperature, $^{\circ}R$
β	relative flow angle (measured from axial direction), deg
η	adiabatic efficiency based on measured total temperatures and total pressures
σ	solidity, ratio of actual blade chord to blade spacing, c/s
$\overline{\omega}$	loss coefficient, $(p_i'' - p_o'')/(p_i'' - p_o)$

Subscripts:

i	inlet
o	outlet
0,1,2,3, 4,5,6,7	measuring stations (see fig. 2)

Superscripts:

' stagnation or total state

" relative stagnation or total state

APPARATUS AND INSTRUMENTATION

The experimental installation used for the 132-percent-turbine survey investigation is the same as that used in the investigations of the 70-, 87-, and 97-percent turbines, as described in reference 8 with modifications given in reference 3. A photograph of the turbine test installation is presented in figure 1. By resetting the stagger angle of the design blade profiles a first-stage stator was obtained having a throat area 132 percent of the design area. This first-stator area (132 percent of design) was selected, since it was the maximum area obtainable with the design blade profiles without moving the throat at the mean blade height upstream of the blade trailing edge.

Figure 2 is a schematic diagram of the turbine showing the axial and circumferential location of the instruments. Radial measurements of total pressure, total temperature, and flow angle were made using combination probes (fig. 3(a)) mounted in remotely controlled movable actuators. With this type of instrument, data were obtained at the turbine inlet (station 1, fig. 2) and at the outlet of each succeeding blade row. At the outlet of each rotor blade row, data were obtained from two actuators located at different circumferential positions. A radial static-pressure distribution at each measuring station was obtained by replacing the combination probes with static-pressure wedges of the type shown in figure 3(b).

METHODS AND PROCEDURE

Turbine matching characteristics for the 132-percent turbine were determined in reference 4, based on an assumed mode of engine operation during which the compressor is maintained at constant equivalent design conditions. The survey investigation of the subject turbine was conducted at an equivalent speed of 2574 rpm and an equivalent work output of 24.22 Btu per pound, which closely approximate the turbine matching requirements of reference 4. The turbine-inlet total pressure and temperature were nominally 35 inches of mercury absolute and 700° R, respectively.

At the outlet of each rotor blade row, as mentioned previously, duplicate sets of measurements were obtained. These measurements were numerically averaged at their corresponding radial positions in order to obtain a single radial trace at each rotor outlet. The parameters used in this report to describe the internal flow conditions of the turbine were calculated by use of the procedures described in reference 9.

RESULTS AND DISCUSSION

The internal flow conditions of the subject turbine are presented in terms of stage work parameter $\Delta T'/T'$, stage efficiency η, and stage Mach numbers and flow angles, each of which is discussed individually. Over-all turbine performance characteristics, based on turbine-inlet and turbine-outlet measurements, are also included. Corresponding results of the survey investigations of the 70-percent turbine (ref. 5), the 87-percent turbine (ref. 6), and the 97-percent turbine (ref. 7) are presented in order that the stagewise radial variations of these parameters with changes in first-stator throat area can be compared. 4519

The data should not be considered quantitative because of the extreme difficulty of obtaining absolute measurements of average flow conditions in the complex flow field between blade rows of a multistage turbine. Secondary flows, circumferential pressure and temperature variations, and other flow distortions cannot be realistically accounted for with only the radial measurements obtained in these investigations. For example, if these flow distortions affected the temperature behind the first stage of the 132-percent turbine so that the measured value of temperature were inaccurate by 1°, a 2-point inaccuracy in the first-stage efficiency would result and the second stage would be inversely affected by 2 efficiency points. Hence, the data should be interpreted only as indicating trends of comparative performance.

Work Parameter

The radial variation of stage work parameter for the subject turbine as well as for the 70-, 87-, and 97-percent turbines (refs. 5, 6, and 7, respectively) is presented in figure 4(a). Because of the divergent passage, percent annular area is used as the abscissa. The radial variation of the over-all work parameter is also shown for all the turbine configurations. The spanwise variations of the work parameter for the first, second, and third stages for the 132-percent turbine are in general similar to those observed in the 87- and 97-percent turbines. Regions of low work parameter occur near the hub and tip of each stage. The radial variation of the over-all work parameter for the 132-percent turbine is similar to that obtained for all three reference investigations. However, the level of the work-parameter curves for all stages and that of the over-all work parameter tend to decrease when the first-stator area is increased.

According to reference 2, as the first-stage-stator area is increased, the match-point equivalent speed and work output requirements are decreased. Since the work output of the turbine is proportional to the work parameter, the work parameter for any stage is proportional to the product of the wheel speed and the change in the tangential component of the absolute velocities entering and leaving the rotor of that stage. For example, it is readily apparent that, if the first-stage-stator area is increased by reorienting the stagger angle of the blades toward axial, the absolute flow angle leaving the stator is decreased. This, in addition to the aforementioned decrease in rotor speed, would then result in a decreased first-stage-rotor entrance tangential velocity. Not much change in the first-stage-rotor exit relative flow angle could be expected, since the geometry is unchanged, but the reduced rotor speed would tend to increase the rotor exit tangential velocity. Although the inlet tangential velocity is decreased as the first-stator area is increased, the exit tangential velocity is increased; and it is believed that the two changes tend to offset each other. The trend noted in figure 4(a) for the first stage, then, is believed mainly attributable to the change in turbine match speed. These same general trends also prevail for the second and third stages to a lesser extent, with the exception of the work-parameter curve for the third stage of the 70-percent turbine, which is considerably higher than the other curves, primarily because this turbine was operating in the immediate proximity of limiting loading. These trends might also be attributed to the match-point speed variation.

The mass-averaged values of the stage work parameter, shown in figure 4(a) for the 132-percent turbine, represent a percentage of the over-all turbine work output. The stage work division and the equivalent match speed and work at which the survey data were obtained for all four turbine investigations are compared in the following table:

Turbine	Stage work division, %			Match operating point	
	First stage	Second stage	Third stage	Equivalent speed, % design	Equivalent work output, Btu/lb
70-Percent (ref. 5)	49.8	20.8	29.4	125	[a]44.38
87-Percent (ref. 6)	47.0	29.7	23.3	102	34.18
97-Percent (ref. 7)	42.9	32.3	24.8	100	32.10
132-Percent	38.6	36.0	25.4	85	24.22

(a) Max. obtainable equivalent work output, as limited by turbine limiting-loading characteristics (ref. 2).

When the throat area of the first stator is at its maximum, the percentage of the over-all turbine work accomplished by the first stage is at its minimum value. Conversely, the percentage work output in the second stage is at its maximum. In fact, there is an 11.2-percent spread in the first-stage work division and a 15.2-percent spread for the second stage for the four turbines investigated. The percentage work output of the third stage remains relatively constant as the first-stator area is varied from 87 to 132 percent of its design value; only when the area is reduced to 70 percent of design is the third-stage work significantly changed, and then by only 6.1 percent from that obtained with the 87-percent turbine. This increased third-stage work output for the 70-percent turbine results from operating the turbine at or very near the turbine limiting-loading condition.

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Efficiency

The radial variation of stage and over-all turbine efficiencies for the 132-percent turbine is shown in figure 4(b). The mass-averaged values are also presented. Included in the figure are corresponding radial efficiency variations from the 70-, 87-, and 97-percent turbine surveys. The levels of the curves show no consistent variation with first-stage-stator area, although all stage efficiencies, as well as the over-all turbine efficiencies, tend to exhibit regions of deficiency near the hub and tip. To better observe the stage and over-all turbine efficiency variations, the mass-averaged values for all four turbines are presented in the following table:

Stage	Stage and over-all turbine efficiencies			
	70-Percent turbine (ref. 5)	87-Percent turbine (ref. 6)	97-Percent turbine (ref. 7)	132-Percent turbine
First	0.900	0.897	0.891	0.850
Second	.759	.843	.849	.815
Third	.828	.755	.784	.784
Over-all	0.865	0.856	0.858	0.831

The individual stage efficiencies vary considerably for any turbine configuration, and the efficiency of any particular stage varies considerably as first-stage-stator area is changed. With all these changes in stage performance, it is significant that the over-all turbine efficiencies vary only about 3 points over the complete range of first-stator areas investigated. That this efficiency spread was small was previously reported in reference 2, where the match-point turbine efficiencies for the 87-, 97-, and 132-percent turbine configurations, as obtained from interpolation of their respective turbine performance maps, were compared. The match-point equivalent work for the 70-percent turbine was unobtainable. The reference turbine efficiencies were based on faired values of torque and weight-flow measurements, and these values were all slightly

higher than the efficiencies obtained in the subject 132-percent turbine survey report and the corresponding survey reports for the 87- and 97-percent turbines (refs. 6 and 7), where the over-all turbine efficiencies were based on the temperature drops across the turbines. The difference of efficiency as calculated by the two methods is mainly attributable to the difficulty of measuring representative average turbine discharge temperatures in the survey investigations. Both methods of calculating turbine efficiencies, however, indicate that the difference in turbine efficiency with first-stator-area configuration is small. Therefore, it can
4519 be concluded that, within the limits investigated and for a mode of engine operation during which the compressor was maintained at equivalent design conditions, the use of adjustable first-stator throat areas had only a small effect on the over-all efficiency of this J71 experimental turbine.

Operational Limitations

Although over-all turbine efficiency is important, other engine operational factors must also be considered before a variable first-stator throat area may be incorporated in an engine design. To better illustrate some of these factors, the same mode of engine operation previously assumed to obtain the compressor-turbine match operating points, that of maintaining constant equivalent compressor design conditions, will be considered.

The ability of the turbine to produce the required work output over the whole range of stator area may be limited. Reference 2 indicates that, if the first-stator throat area is reduced to less than about 75.5 percent of the design area, the subject turbine would be unable to drive the compressor for the mode of engine operation considered.

Mechanical considerations such as the turbine blade centrifugal-stress level and operational temperature are also important limiting factors. For the mode of operation considered, operation at constant turbine-inlet temperature over a range of compressor-inlet conditions (corresponding to varying flight Mach number and altitude) results in a variation of engine rotative speed. With 75.5 percent of design first-stator area being considered the lower limit of area variation, the turbine match-point equivalent rotor speed would be about 116 percent of design (see fig. 10(b) of ref. 2); and, with a constant turbine-inlet temperature, the mechanical rotor speed would also increase to 116 percent of design. Since turbine blade centrifugal stress is directly proportional to the square of the rotative speed, operation of the turbine with this first-stator area would result in an increase of about 35 percent over the design turbine stress. That this stress increases as the throat area decreases from that of design may further restrict the lower limit of first-stator area variation.

The maximum permissible first-stator throat area may be restricted by turbine-inlet temperature. Operation with areas greater than design requires an increase in the engine temperature ratio in order to maintain constant equivalent compressor design conditions. Figure 9(b) of reference 2 shows that the turbine with the 132-percent first-stator area requires an engine temperature ratio (turbine inlet to compressor inlet) of about 5.7. Assuming a moderate flight condition, such as engine operation at a Mach number of 0.5 in the stratosphere, the compressor-inlet total temperature would be approximately 412° R. With an engine temperature ratio of 5.7, then, the turbine-inlet temperature would be approximately 2350° R, certainly not conservative by current turbojet standards. Furthermore, if either the flight speed is increased or the flight altitude is decreased (still maintaining constant equivalent compressor design operation and a fixed turbine first-stator area), the required turbine-inlet temperature would increase further. Hence, turbine-inlet temperature will restrict the upper limit of first-stator-area adjustment unless some method of cooling the turbine blades is incorporated in the design of variable-first-stator-area turbines.

It can be concluded, then, that considering only the turbine aerodynamic performance, the use of adjustable turbine stator area for the subject turbine appears to be a feasible method of permitting constant equivalent design-point compressor operation over a wide range of off-design turbine conditions. Other turbine operational factors must be considered, however, which may limit the amount of allowable first-stator-area adjustment.

Interstage Flow Velocities and Angles

The radial variations of the absolute and relative Mach numbers and flow angles entering and leaving each rotor blade row for the subject turbine and the three reference turbines are presented in figure 5. The radial variations of the design values obtained from the design velocity diagrams presented in reference 9 are also included. Angles in the direction of rotor rotation are defined as positive. Figure 5(a) indicates that the absolute and relative Mach numbers at the inlet of the first-stage rotor for the 132-percent turbine are considerably lower than the design values and lower than those observed in the three reference turbines, as was expected. The absolute flow angle at the first-rotor inlet is underturned from design on the order of 12° over most of the blade span, reflecting the change in first-stator stagger angle. The relative flow angle at the inlet to the first rotor indicates that a negative angle of incidence, defined as the deviation from the design angle, on the order of 20° over most of the blade height is present on the first-stage rotor. The Mach numbers and flow angles at the outlet of the first rotor (fig. 5(a)) are of the same order of magnitude as those observed in the three reference investigations. However, the outlet absolute flow angle is considerably closer to the design value, indicating very small angles of incidence on the second-stage stator.

Figure 5(b) shows that the absolute and relative Mach number distributions at the inlet and outlet of the second-stage rotor are similar to those observed in the reference turbines. However, the level of the curves is slightly lower, in general, than was previously noted. The absolute and relative flow angles at the inlet and outlet of the second-stage rotor are similar in distribution and magnitude to those observed in the 87- and 97-percent turbines. The rotor inlet relative flow angle indicates that it is operating with negative incidence on the order of 4° near the blade hub to positive incidence angles of about 6° to 8° in the tip region.

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The radial variations of the Mach numbers and flow angles at the third-stage-rotor inlet and outlet for all four turbine configurations also have similar trends (fig. 5(c)). The levels of the Mach number curves for the 132-percent turbine are lower than those observed in the reference turbine investigations. The relative flow angle at the third-rotor inlet indicates that the rotor is operating with positive incidence on the order of 10° over most of the blade height. The flow angles at the outlet are near the design values.

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Loss Function

Figure 6 presents the radial variation of the stage loss function $(\bar{\omega} \cos \beta)/\sigma$ (described in detail in ref. 9) for each turbine stage for the subject turbine as well as for the 70-, 87-, and the 97-percent turbines (refs. 5 to 7). The loss parameter $\bar{\omega}$ is the relative total-pressure drop across the rotor divided by the difference between the rotor inlet relative total pressure and the static pressure at the rotor outlet. No total-pressure loss is assumed to occur in the stator. The trends of the curves for each stage of each turbine exhibit similar characteristics. Regions of highest loss parameter still persist in the hub and tip portions of the blades.

SUMMARY OF RESULTS

A cold-air radial survey investigation of the J71 experimental three-stage turbine with a first stator having a throat area 132 percent of design was conducted at a predetermined turbine operating match point. Individual stage performance characteristics were determined. The results were compared with corresponding results previously obtained with the same turbine having first-stator throat areas of 70, 87, and 97 percent of design. The following results were obtained:

1. The mass-averaged values of the first-, second-, and third-stage efficiencies for the 132-percent turbine were 0.850, 0.815, and 0.784, respectively. Regions of deficiency existed near the hub and tip for all three blade rows.

2. The individual stage efficiencies varied considerably for each of the four turbine configurations investigated. Also, the efficiency of any particular stage varied widely as the first-stage-stator area was changed. The over-all turbine efficiency, however, varied only about three points over the wide range of first-stator areas investigated.

3. Although the Mach numbers and flow angles at the outlet of the first stator of the 132-percent turbine were considerably lower than the design values, as would be expected, the trends of the distributions at the outlet of succeeding blade rows were, in general, similar to those observed for the 70-, 87-, and 97-percent turbine configurations. 4519

4. Considering the turbine aerodynamic performance, the use of adjustable turbine stator area appears to be a feasible method of permitting constant equivalent design-point compressor operation over a wide range of off-design turbine conditions. However, operational factors such as turbine work limitations, turbine rotor blade centrifugal stress, and turbine-inlet temperature may limit the amount of first-stator-area adjustment allowable.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 3, 1957

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Figure 1. - Installation of J71-132 experimental three-stage turbine in full-scale turbine-component test facility.

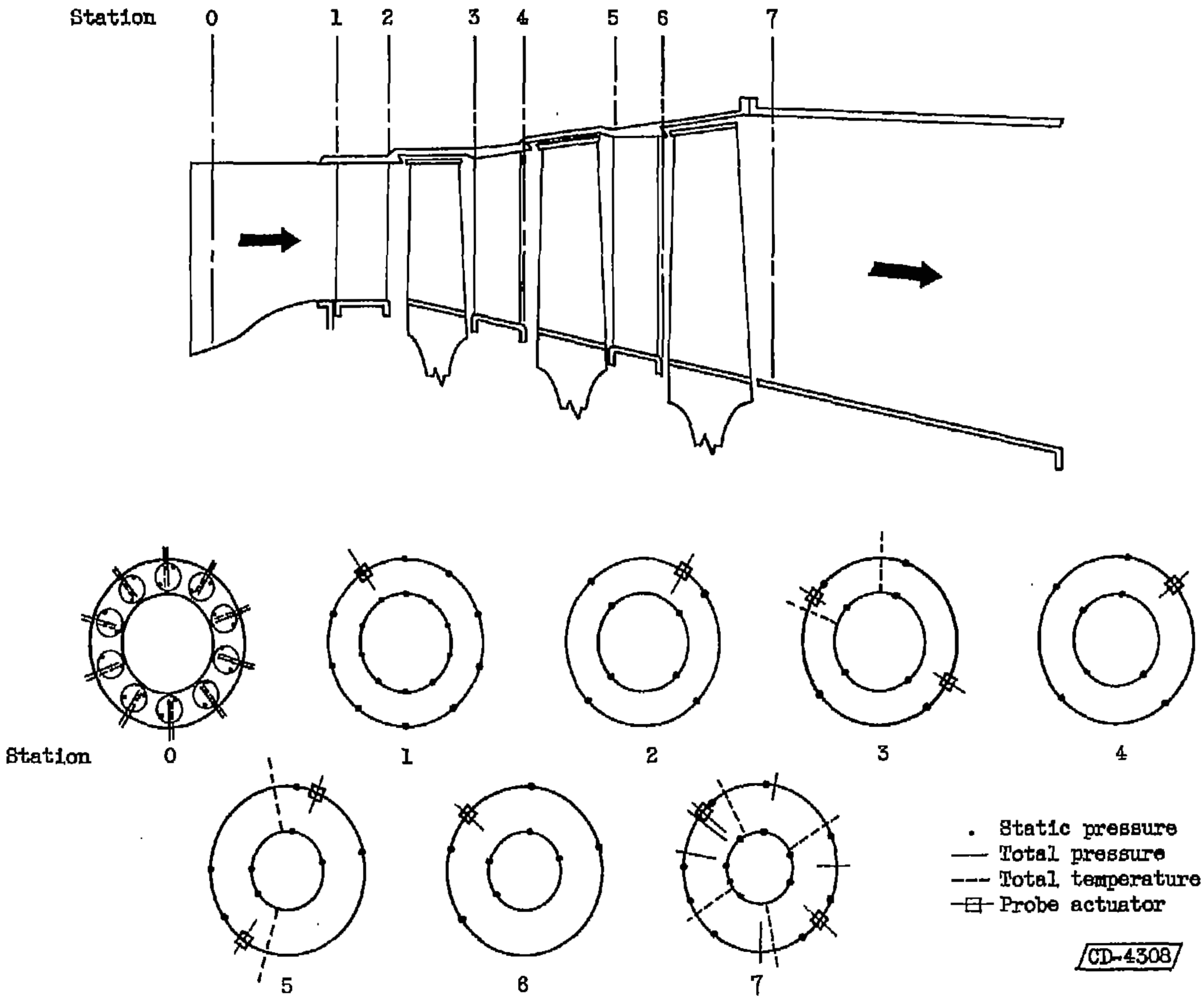
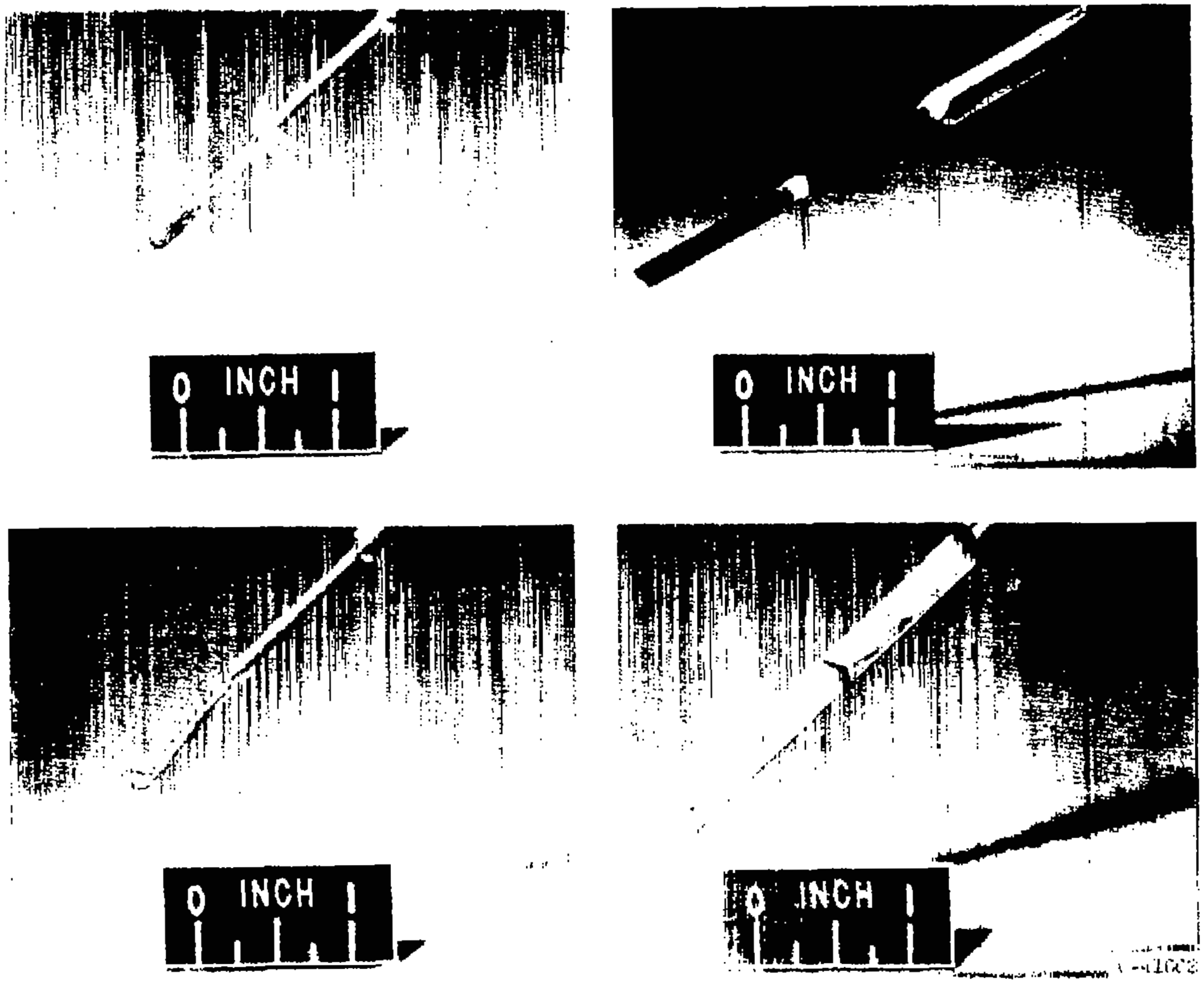


Figure 2. - Schematic diagram of J71-132 turbine showing instrumentation.



(a) Total-pressure, total-temperature, and angle probe.

(b) Static-pressure wedge.

Figure 3. - Typical static-pressure wedge and combination probe for measuring total pressure, total temperature, and angle.

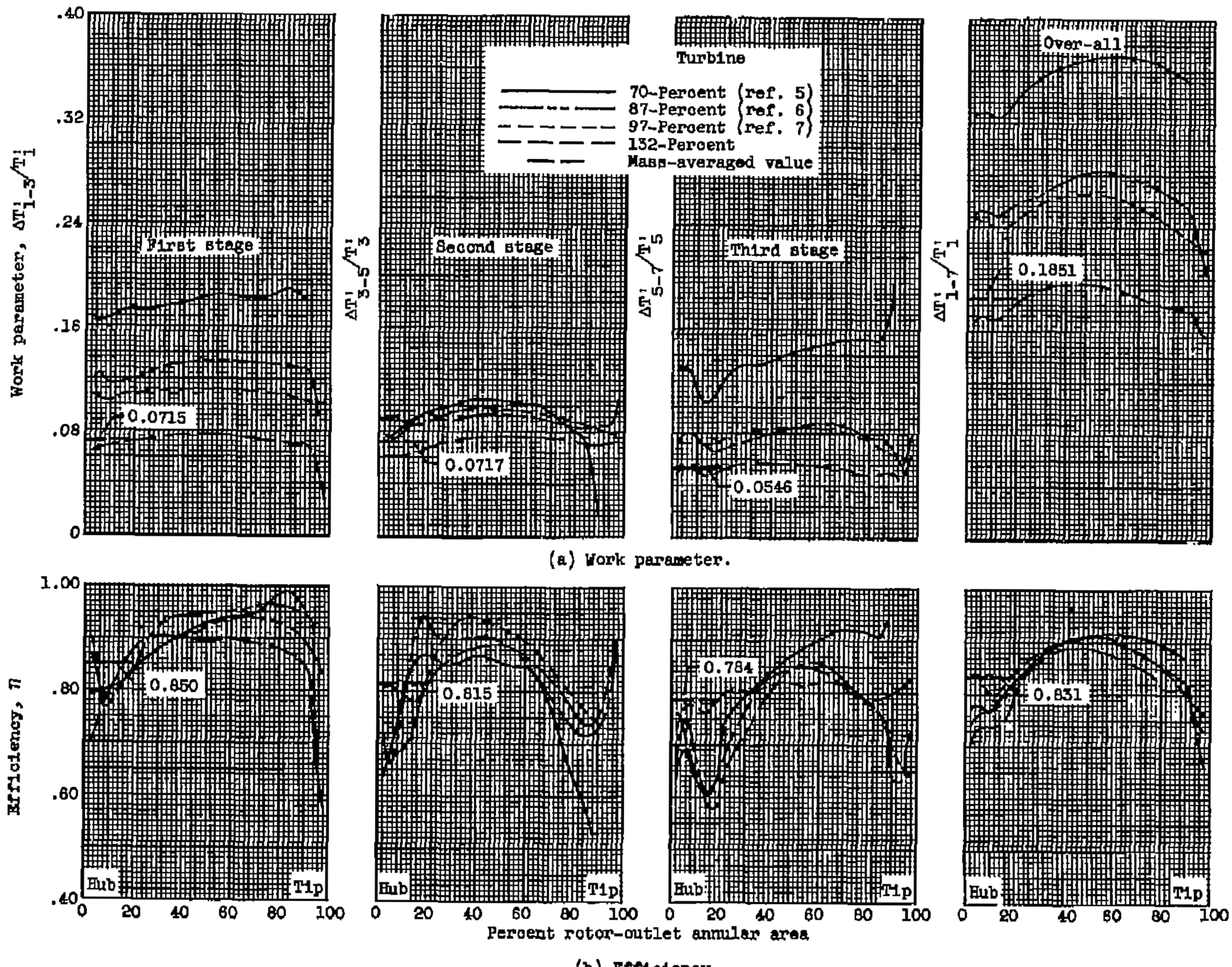


Figure 4. - Variation of stage and over-all work and efficiency with annular area at rotor outlets.

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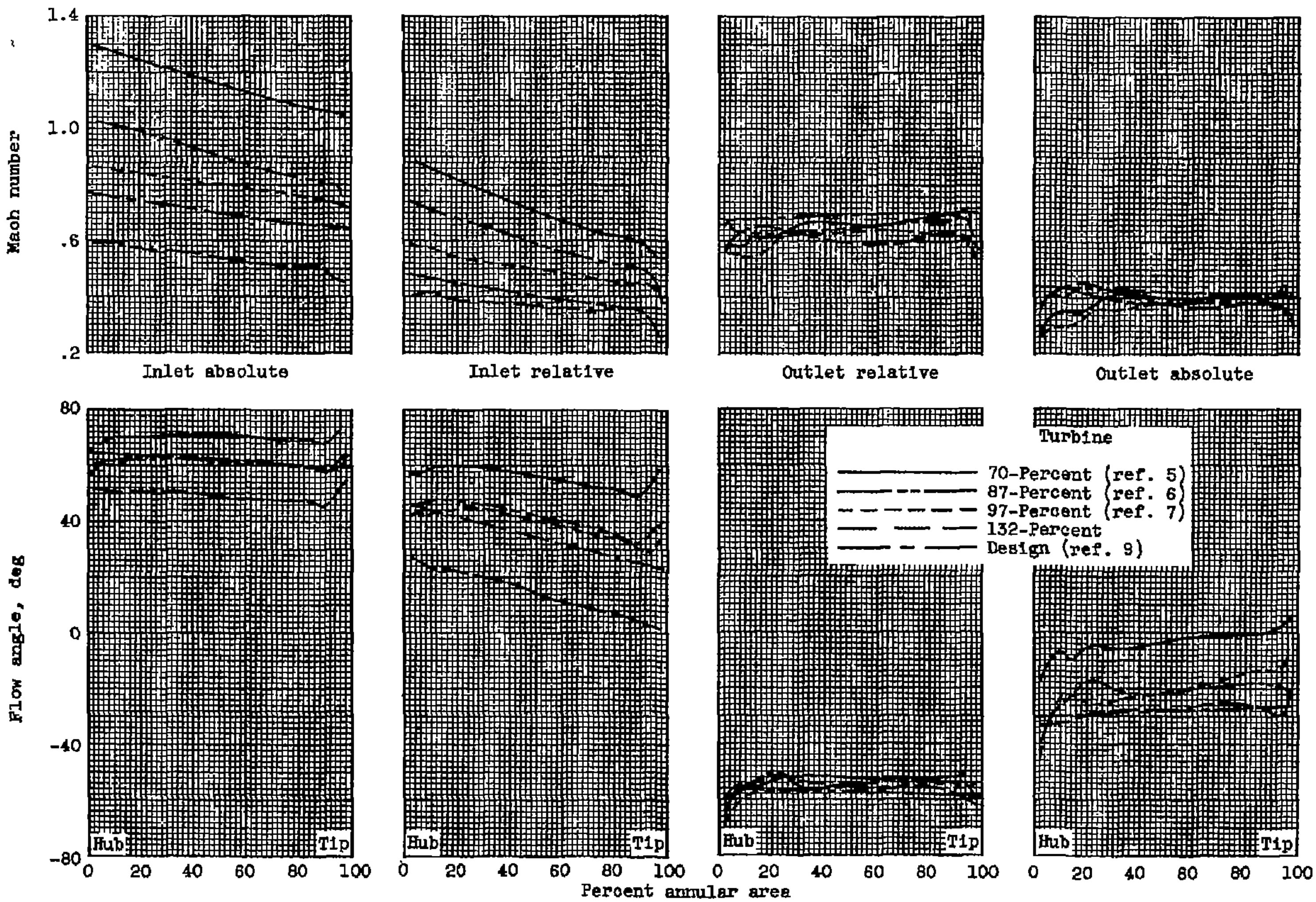

(a) First rotor.

Figure 5. - Variation of absolute and relative Mach number and flow angle at rotor inlet and outlet with annular area.

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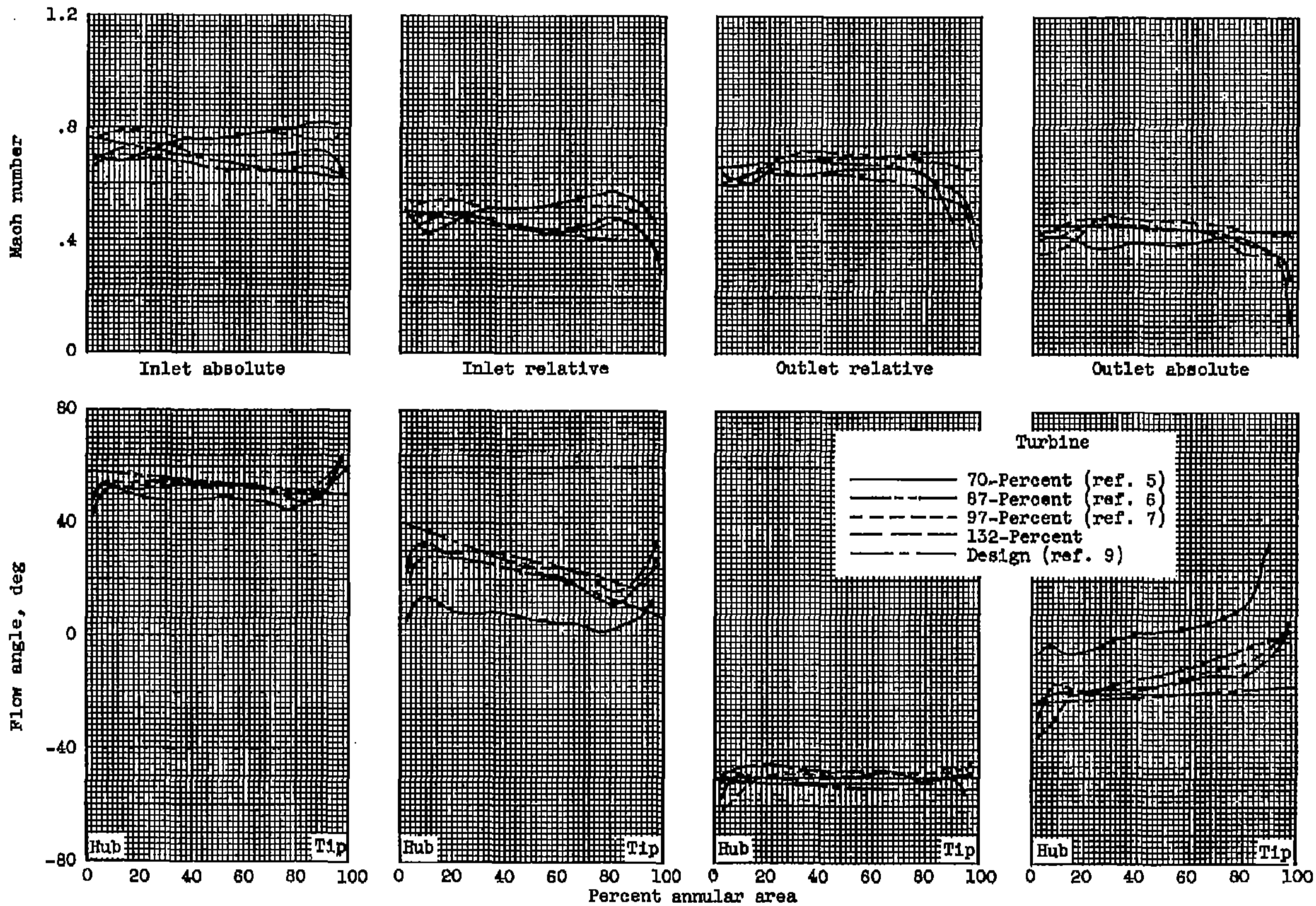

(b) Second rotor.

Figure 5. - Continued. Variation of absolute and relative Mach number and flow angle at rotor inlet and outlet with annular area.

[redacted]

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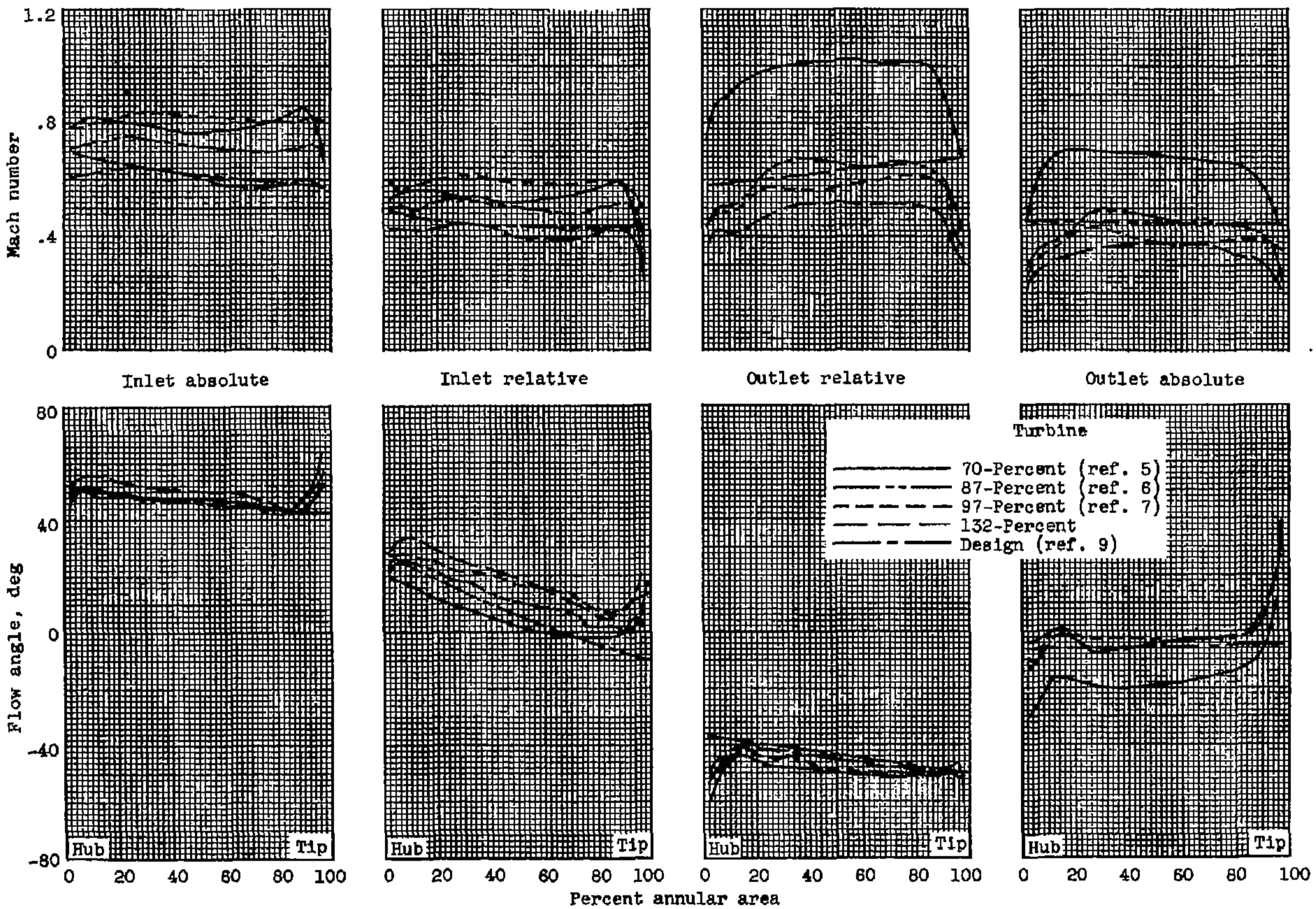

(c) Third rotor.

Figure 5. - Concluded. Variation of absolute and relative Mach number and flow angle at rotor inlet and outlet with annular area.

[redacted]

[redacted]

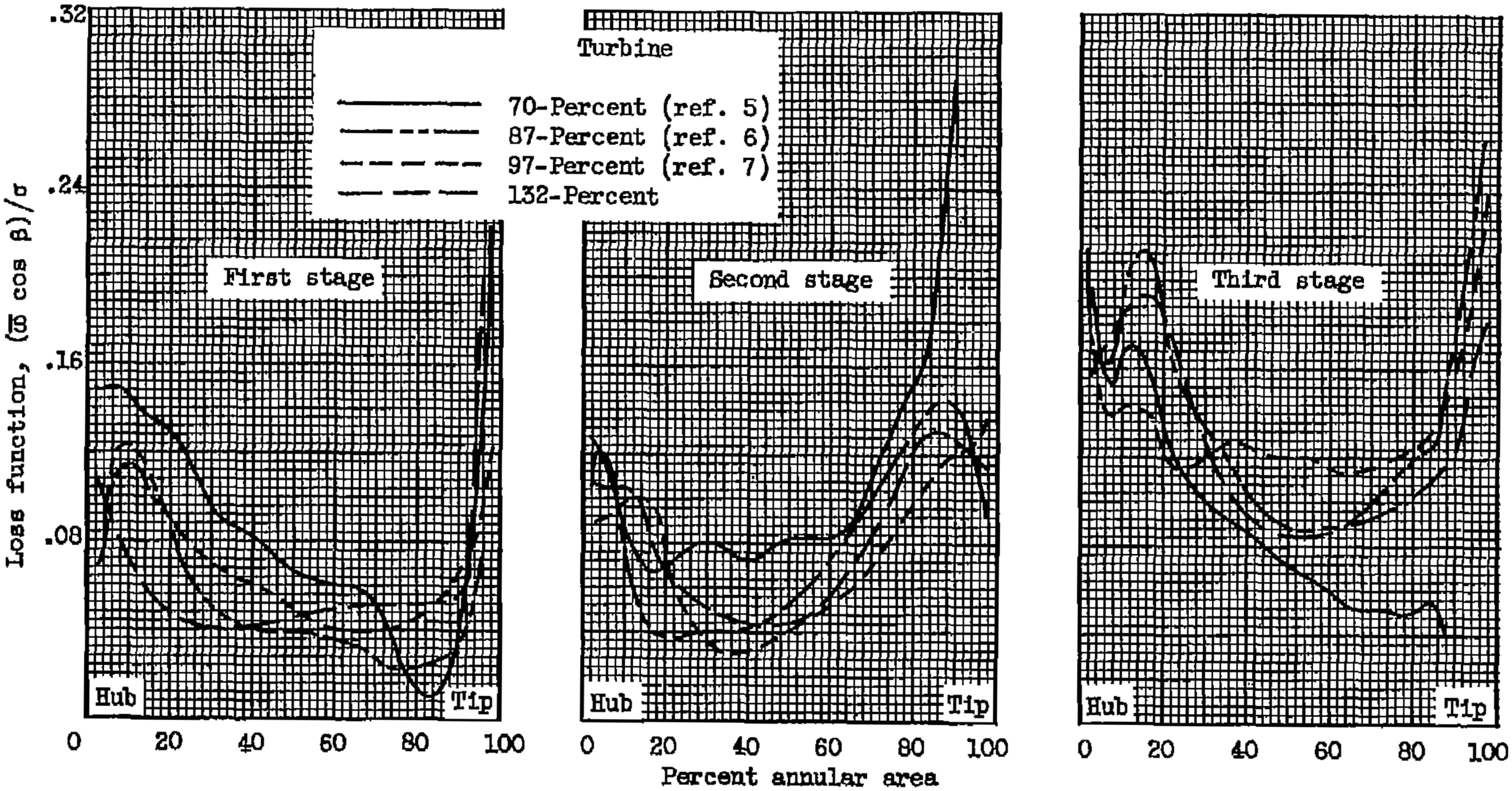

Figure 6. - Variation of loss function with annular flow area.

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